Land Effects on TOPEX Radar Altimeter Measurements in Pacific Rim Coastal Zones

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Satellite radar altimetry is potentially a very useful tool for remote sensing in support of Pacific Rim coastal zone management. Just as in the open ocean, the altimeter data in the coastal zone can provide valuable information on wave heights, structure of the geoid (and the associated gravity field), and dynamic sea surface topography resulting from tides, winds, currents, and atmospheric pressure. Because of this wealth of information, oceanographers seek to extend the use of altimeter data to the shoreline. Users of the altimeter measurements in the coastal zones need to be aware, however, that measurement quality may be affected by land when a satellite groundtrack is within a few kilometers of land. It is shown that waveform retracking can extend the altimeter-derived sea surface topography several kilometers shoreward.

1 INTRODUCTION

As part of our ongoing TOPEX performance assessment program at NASA Goddard Space Flight Center's Wallops Flight Facility, we have examined the effects of nearby land (continental coastlines and islands) on the TOPEX altimeter's measurements. In the course of our analysis, we have studied offshore altimeter measurements in close proximity to a variety of terrain including mountains, lowlands, hills and islands.

Guidelines for data users to assess the data quality, when using TOPEX altimeter measurements in close proximity to land, have been developed and are discussed. Techniques are also presented such that the data user may rectify some of the affected data, and recover the sea surface topography.

2 BACKGROUND

2.1 Altimeter Description

TOPEX is a dual-frequency (Ku- and C-Band) radar altimeter with complete redundancy of all active circuitry. It is a nadir-looking radar which transmits RF energy towards the earth's surface, then receives and processes the reflected energy. It measures height above

the earth's surface (pulse transmit time), ocean significant waveheight (via return pulse shape characteristics), and surface radar backscatter coefficient (via received energy).

The TOPEX radar altimeter, at Ku-Band, has an antenna beamwidth of 1.0 degree. This beamwidth, coupled with an average altitude of about 1339 km, provides a waveform-sampled footprint with a radius R of 11.0 km, derived as:

$$R = (hc\tau)^{1/2} \text{ (Chelton } et\ al, 1989)$$

where h is the altimeter height in kilometers, c is the velocity of propagation in km/ns, and τ is the separation between the waveform tracking gate (24.5) and the last waveform gate (64) =301.56 ns.

As the TOPEX footprint approaches land, the earliest that land returns can appear in the altimeter waveform is thus 11.0 km from land. Even then, land returns will not appear in the waveforms until there are terrain facets oriented such that sufficient radar energy is backscattered toward the altimeter.

The altimeter tracker itself operates with a smaller footprint radius of about 6.3 km, based on the 32-sample width of the AGC gate. The radar returns from the larger waveform-sampled footprint are used in determining the altimeter's off-nadir angle (attitude), and it is this larger footprint which is referred to in the remainder of this report.

The groundtrack velocity of TOPEX is 5.8 km per second. The groundtrack pattern repeats, within ±1 km, every 9.92 days. Additional information on the TOPEX radar altimeter is in Zieger *et al* (1991).

2.2   Land Reflections in the Altimeter Waveforms

The digital filter bank (DFB) lies at the heart of the altimeter and its range tracking loop. The transmitted pulse (320 MHz chirp bandwidth, 102.4 μsec pulsewidth, from the digital chirp generator) scatters off the ocean surface; the received return signal is dechirped and then mixed down to in-phase and quadrature signals, filtered with a 625 kHz lowpass filter, and digitized at a 1.25 MHz sample rate. At 1.25 MHz, the 102.4 μsec pulse results in 128 complex samples upon which the DFB performs a 128-point fast Fourier transform (FFT). The FFT output is 128 individual waveform samples, spaced 9.765 kHz apart in frequency (equivalent to 3.125 ns spacing in the time domain), which are tracked by the adaptive tracker unit.

Prior to downloading the tracking data, the onboard computer compresses the waveforms, at the rate of ten per frame for Ku-Band and the rate of five per frame for C-Band. For the altimeter's Track Mode, of interest here, the waveform's 128 samples are compressed into 64 gates as follows:

• Gates 1-8 are averages of successive pairs of samples 1-16. Each gate width is 6.250 ns, or 93.685 cm in range equivalence.

• Gates 9-40 (the AGC Gate) are one-to-one representations of samples 17-48. Each gate width is 3.125 ns, or 46.843 cm in range equivalence.

• Gates 41-48 are averages of successive pairs of samples 49-64. Each gate width is 6.250 ns, or 93.685 cm in range equivalence.

• Gates 49-64 are averages of successive sets of four samples, from 65-128. Each gate width is 12.500 ns, or 187.370 cm in range equivalence.

TOPEX waveform descriptors can thus be either in terms of 128 samples or 64 samples. Since the TOPEX Sensor Data Records (SDR) waveforms are available only as 64 samples, it is those compressed waveforms which are discussed in this report.

As a general statement, whenever land is within 11.0 km of the altimeter nadir point, as depicted in Figure 1, there is a likelihood that land reflections will appear in the altimeter waveforms. Depending on the type of shoreline terrain, land reflections may not appear until the nadir point is closer to the shoreline.

Water-to-Land - In successive waveforms, as the altimeter approaches land, the land reflections move from the late gates into the AGC gate. Even though the altimeter's nadir point is over the sea, the tracker responds to the brighter reflections from the land within the AGC gate, and begins to track those off-nadir returns; this is because tracking is done by comparing the middle gate (in effect, the nadir return) to the AGC gate. As a result, the waveforms will become misaligned with respect to the onboard tracking gate, the measured range near land will be too long, and the calculated at-nadir sea surface height will be too low. The waveforms may be retracked to recover the true range to the at-nadir sea surface.

Land-to-Water - As a groundtrack goes from land to water, the altimeter generally starts off by tracking the brighter off-nadir land reflections, again resulting in misaligned waveforms and range measurements which are too long. As the altimeter moves further from land, the land reflections move towards the later gates, and the altimeter begins to track the at-nadir sea surface.

In the TOPEX ground processing, there are corrections made to the range measurements; some of these corrections are functions of the SWH and the attitude derived from the footprint. Whenever land returns appear in the late gates of the altimeter waveform, the attitude cannot be adequately estimated from the waveforms.

The TOPEX Ku-Band waveforms, at the rate of ten per frame (approximately ten per second), are available in the SDR files maintained by the TOPEX Project. During the routine telemetry processing of the TOPEX measurements, a waveform shape discriminator algorithm flags those misshaped and/or misaligned waveforms which have land returns. When the waveforms are flagged by this algorithm, bit 2 of the Alt_Bad1 flag in the TOPEX Geophysical Data Record (GDR) is set. For example, the upper waveform in Figure 2 is a normal-appearing unflagged Ku-Band full-rate open-ocean waveform from Cycle 075 Pass 010. This waveform occurs 8.6 km from the mountainous shoreline of New Zealand's South Island, as the altimeter is approaching the island. The misshaped flagged lower waveform in Figure 2 occurs 0.43 seconds later, when the altimeter is 6.1 km from the shoreline; the sharp peak near waveform gate 50 is a land return. The waveforms in this report, such as in Figure 2, are plotted as counts (amplitude) versus the sampling gates numbered 1-64.

The Alt_Bad1 flag is set for an entire frame, even though only a portion of that frame's waveforms may have been corrupted by land returns. It is likely, therefore, that the measurements will be flagged at a distance beyond the presence of land returns in the waveforms.
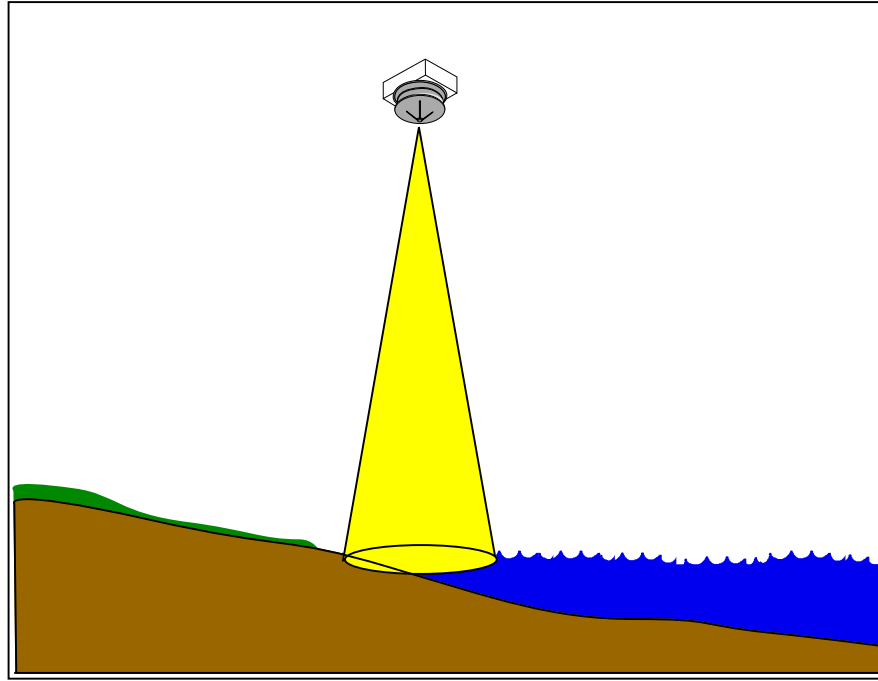
Figure 1: Altimeter's Waveform-Sampled Footprint Near Land

The TOPEX altimeter also produces C-Band waveforms, at the rate of five-per-frame. This report doesn't discuss the C-Band waveforms because they essentially mimic the Ku-Band waveforms and they are at the lower rate.

3 Use of Near-Land Altimeter Data

The land effects differ somewhat, depending on whether the altimeter groundtrack is approaching land or it is receding from land. The difference is due primarily to the altimeter being in Track Mode over the sea surface prior to the water-to-land transition, while in the land-to-water scenario, the altimeter is often not in normal Track Mode over the land. The reacquisition of the signal over the ocean after a water-to-land transition consumes a second or more of time. As a result, the sea surface topography is generally recoverable closer to the shoreline when the groundtrack is approaching land.

The GDR files directly provide sea surface heights (SSH) at the rate of one-per-frame (approximately one-per-second). For near-land studies, the SSH rate can be increased to ten per frame by adding, to the frame-average SSH, each of the ten per frame height differences labeled SS_Hght_Hi_Rate in the GDR file. The ten per frame time-tags and the ten per frame latitude/longitude coordinates to be associated with the high-rate SSH may be calculated, using the fact that the time-tag and the latitude/longitude for each frame in the GDR is referenced to the middle of the frame.
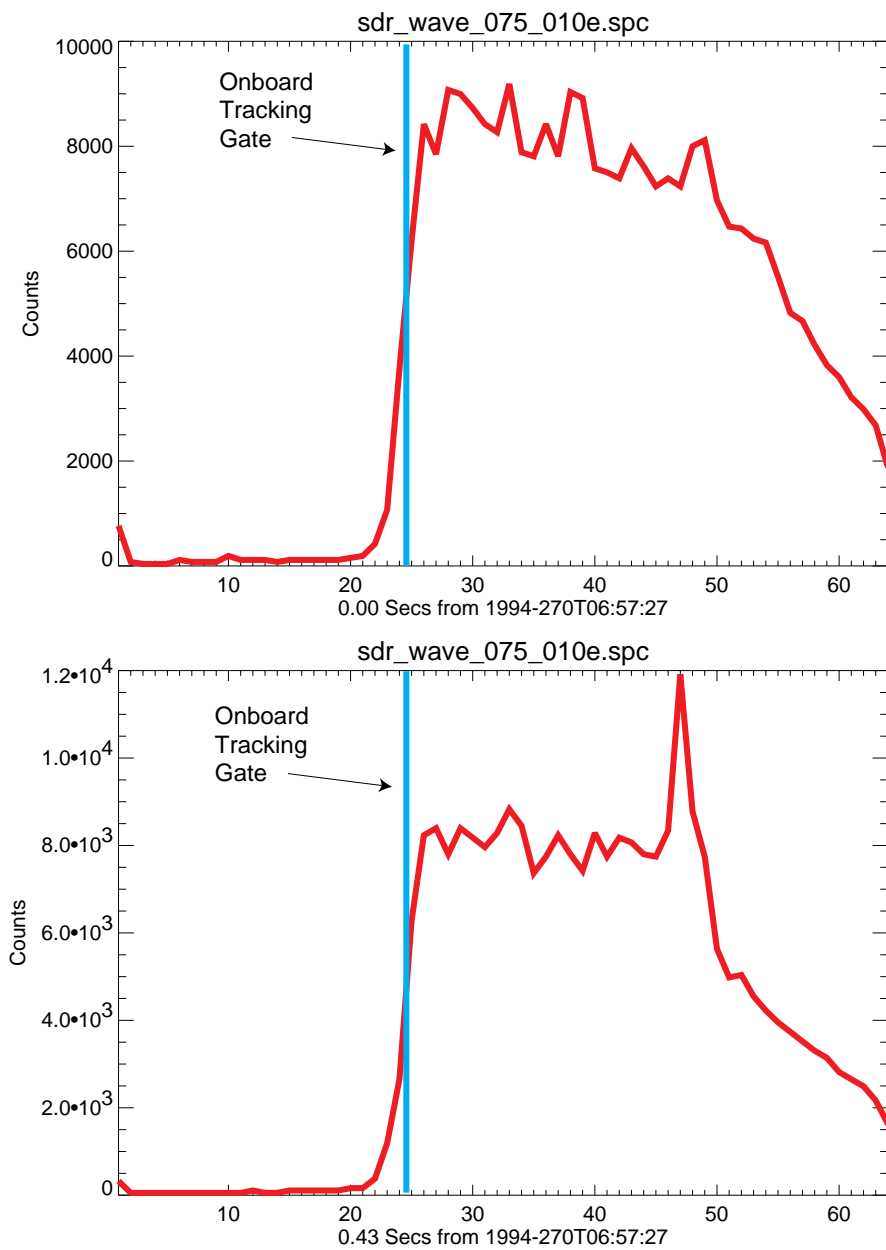
Figure 2: TOPEX Waveforms from Cycle 075 Pass 010 With and Without Land Reflections

The most conservative approach for the GDR user to using near-coastal data from the TOPEX altimeter is simply to eliminate all data which have the Alt_Bad1 flag set. If this flag is not set, the GDR data can be expected to be valid.

If the user has an interest in using data closer to land, the following steps are recommended. When bit 2 of the Alt_Bad1 Flag in a GDR frame is set, it means that some or all the ten Ku-Band waveforms in that frame are misshaped or misaligned, or both. Also, when this flag is set, the correction to range for the effects of significant wave height and for attitude, DR(SWH/Att)_K, for that whole frame has not been calculated and has been set to zero during the ground processing. It also means that the range correction for the ionosphere (Iono_Corr), which is based in part on DR(SWH/Att)_K, will be erroneous.

1. Obtain the Sensor Data Record (SDR) file for the particular cycle/pass. The SDR files, maintained by the TOPEX Project at JPL, contain the full-rate waveforms. The SDR files also contain, for reference, Waveform_Flags_Hi which provides information on which individual waveforms within a frame are flagged and the reason(s) for the flagging (Callahan, 1993). For this study, we used waveforms directly from the SDR files; for further refinement, it is recommended that the user employ the the waveform per-gate multiplicative and additive factors from Hayne *et al* (1994).

2. Retrack the individual Ku-Band full-rate waveforms, calculating the number of gates and decimal gates (to 0.001 gates) to be shifted to realign the leading edge of sea surface returns. Retracking is defined here as post-flight alignment of selected waveform attributes with respect to a particular sampling gate, and the concomitant change in range. For the retracking, recall that gates 1-8 and 41-48 have separations of 6.250 ns (93.685 cm), gates 9-40 have separations of 3.125 ns (46.843 cm), and gates 49-64 have separations of 12.500 ns (187.370 cm). These differences in gate separations are the primary reason that, in the figures in Section 4.2 below which contain successive waveforms, the land returns move more slowly through the late gates than the middle gates. For the retracking, we recommend a threshold technique which is described in Section 4.

3. Apply the calculated range-correction per waveform to the corresponding full-rate SSH from the GDR. If the range correction is such that it shortens the range, the corrected sea surface height will be higher, and vice-versa.

4. Both the altimeter's mistracking and the zero-setting of DR(SWH/Att)_K introduce errors to the frame-value for Iono_Corr, the range correction for ionospheric delay. For each of the frames with bit 2 of the Alt_Bad 1 set, algebraically add the GDR-provided Iono_Corr for that frame to the SSH for the frame. Then algebraically subtract from the SSH the Iono_Corr from the closest open-ocean frame on that same pass which has a valid Iono_Corr. The ionospheric correction is not expected to change significantly over a few kilometers. The magnitude of the Iono_Corr is typically several centimeters.

4 Waveform Retracking

The concept of retracking satellite altimeter waveforms is not new; various investigators have been retracking waveforms since the early 1980's. Until recently, waveform retracking has been performed primarily to recover surface elevations over ice sheets (e.g., Martin et al., 1983, and Ridley and Partington, 1988) and land (e.g., Brooks and Norcross, 1983). Retracking over ice and land is necessary because the onboard tracking systems on the altimeters are optimized for ocean returns, and are not fully responsive to waveforms from the larger terrain undulations and from the more specular surfaces. Altimeter range measurement errors over land can easily build up to the level of several meters.

Retracking has more recently been extended to over-ocean waveforms (e.g., Hayne and Hancock, 1990, Brenner et al., 1993, and Rodriguez and Martin, 1994). Over-ocean measurement improvements from retracking are typically on the order of one centimeter.

All the prior published retracking efforts have, to our knowledge, involved the retracking of over-ocean or over-land waveforms which have each been averaged over a time interval of about one second. This study differs from previously published work in that we are using the full data rate of ten waveforms per second, and because we are attempting to retrack "hybrid" waveforms, i.e., part of the waveform is based on ocean returns and part on land returns. It is noted that Rodriguez and Martin (personal communication, 1997) have performed some full-rate near-shoreline waveform retracking studies for a variety of terrain types, but they have no imminent plans to publish their results.

4.1 Waveform Retracking Method

As the groundtrack gets closer to land (within the 11.0 km radius footprint), the land returns begin to be the prominent feature in the waveforms. As long as the at-nadir distance to the ocean surface is shorter than the off-nadir distance to the radar-reflecting land features, the ocean returns will appear earlier in the waveform. As the land returns enter the AGC gate, the altimeter tracker tends to start tracking the off-nadir land. As a result of the longer range measurement to land, the calculated at-nadir sea surface height will be too low.

The at-nadir sea surface heights may be recovered by retracking the full-rate waveforms, as long as the sea surface return at the beginning of the waveform is discernible. Such a shifted full-rate Ku-Band waveform is shown in the lower half of Figure 3; this waveform, from Cycle 137 Pass 095, occurred 2.0 km from the shoreline of Vancouver Island, British Columbia. In this waveform, the sea surface return appears in gates 11 through 14, while the land returns dominate the later gates of the waveform. A normal open-ocean waveform from this same pass, occurring 1.62 seconds earlier at a distance of 11.4 km from land, appears at the top of Figure 3.

For all the passes examined in this study, a threshold retracker was employed. For our retracking near land, a threshold value for each pass was selected such that the threshold was higher than both the noise and the minor waveform leakage in the early gates, and which was sufficiently low to intercept the sought-after ocean returns. Our threshold levels
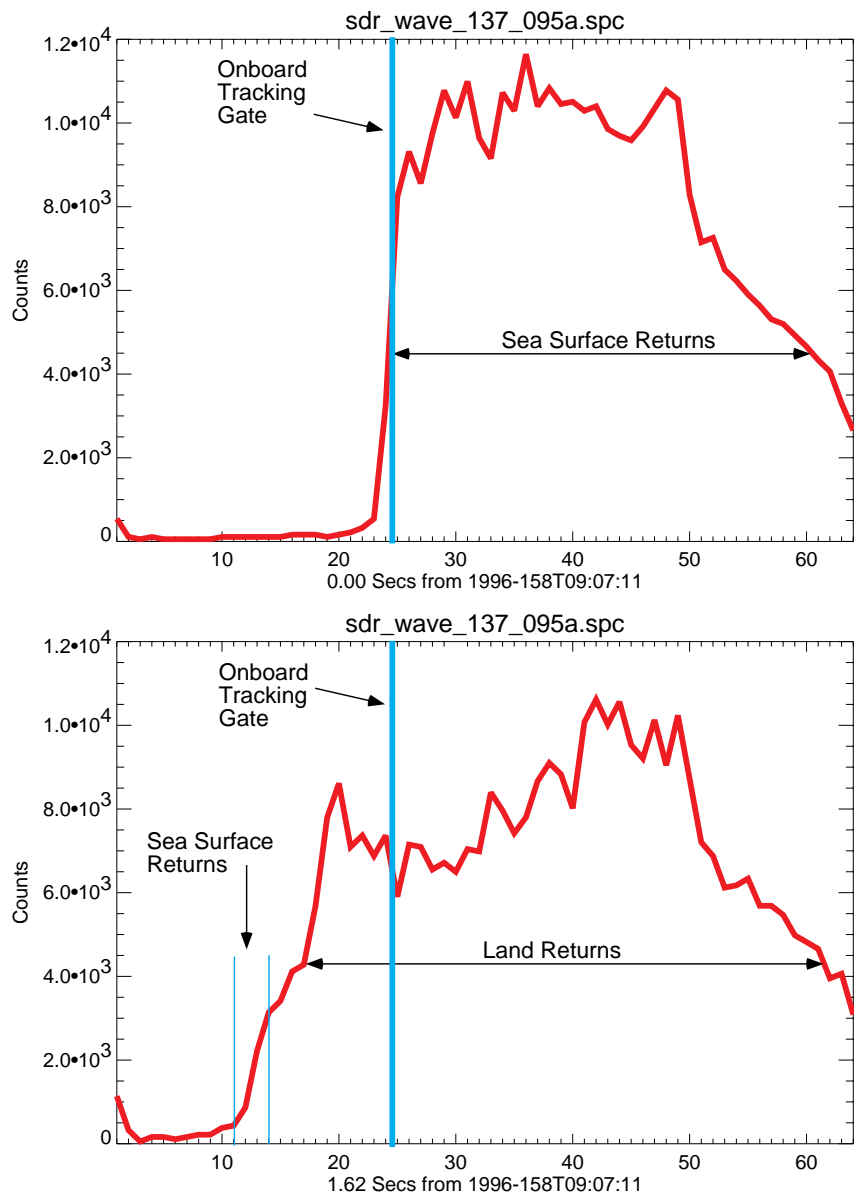
Figure 3: Two Waveforms, Aligned (top) and Misaligned (bottom), with Respect to the Tracking Gate

for retracking varied from a low of 500 counts for both Chile and China's Shandong Province, to a high of 2500 counts for Japan's Honshu Island. For the waveforms approaching Vancouver Island, a threshold of 1500 counts was selected. In the near-Vancouver Island waveform shown in the lower part of Figure 3, for example, the threshold value of 1500 intercepted the ocean return at the interpolated gate number of 12.283. An automated method for selecting a threshold level remains a goal for future work.

Then, several seconds of open-ocean no-land waveforms (same area, same pass of data) are used to ascertain the average, normal intercept of n counts with the ocean return. For the Vancouver Island pass, the average 1500-count intercept for normal waveforms was gate 23.318. The range difference between the two intercepted gates is 46.843 cm per gate times [23.318 - 12.283], or 5.169 m. This difference gets added to that waveform's corresponding full-rate sea surface height which is on the GDR. Then the corrected Iono_Corr was applied.

For our retracking, we had an option of retracking only the one or two frames of affected waveforms, or to extend the retracking seaward into unflagged frames. The latter option was chosen to maintain a consistent measurement noise level across the entirety of the sea surface profile. For each frame that is retracked, negate the effects of the GDR-applied DR(SWH/Att)_K by algebraically adding its value to the SSH; this needs to be done because the retracking essentially replicates the DR(SWH/Att)_K.

We plan to perform in-depth error and noise analyses of the resultant sea surface heights in the near future, but it is evident, as shown in Section 4.2, that the retracking significantly improves the near-land altimeter-derived sea surfaces.

4.2 Examples of Waveform Retracking Results

For this study, nine water-to-land and nine land-to-water transitions were examined, at locations scattered around the Pacific Rim. Two examples for each of the water-to-land and the land-to-water scenarios are discussed below. For each of the examples, a sequence of twenty successive (two frames) of full-rate near-coastal Ku-Band waveforms is presented - the accompanying waveform descriptions in the text are based on a visual interpretation of each of the individual waveforms.

WATER-TO-LAND

Borneo (Subdued Topography)

As the altimeter groundtrack is over the Java Sea, approaching the marshes of southern Borneo from the southeast (Figure 4), the land reflections initially appear in the late (higher numbered) gates, and in succeeding waveforms, move closer to the tracking gate (halfway between gates 24 and 25). This movement is shown in the twenty successive full-rate waveforms in Figure 5, from Cycle 135 Pass 051. The waveform sequence in Figure 5 is left-to-right and then top-to-bottom. The location of this span of twenty waveforms is indicated on the map in Figure 4.

Waveform 1 of Figure 5 occurs when the groundtrack is 9.6 km from land, and the land reflection is just appearing in the late gates, in the vicinity of gate 60. There is static waveform leakage near gate 48 which needs to be differentiated from the land reflection. As indicated in the figure, it is also at waveform 1 that bit 2 of Alt_Bad1 was set. In wave-
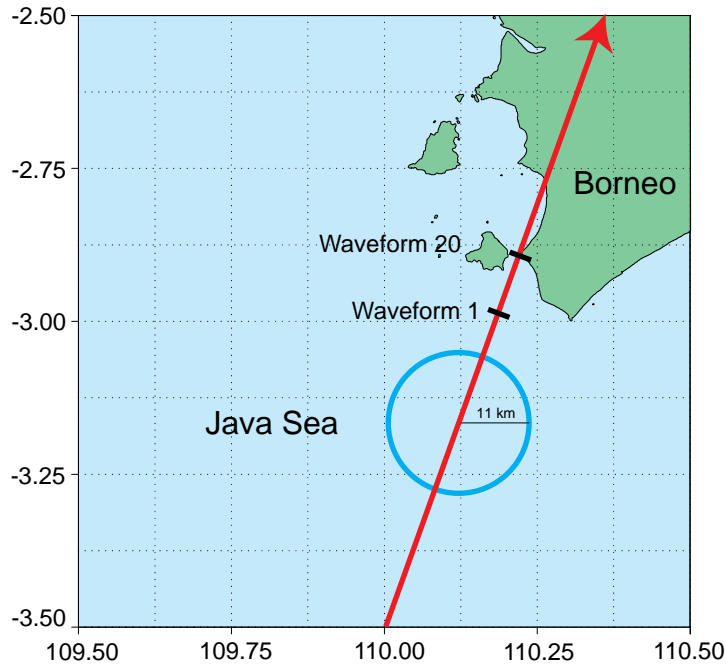
Figure 4: Cycle 135/Pass 051 - Approaching Southern Borneo

forms 2 and 3, the land return is in the vicinity of gates 57 and 55, respectively. In the successive waveforms, the land returns moves closer to the tracking gate. In the twelfth waveform, the ocean return is discernible near the tracking gate, while the land return begins near gate 32. The ocean return remains barely visible for the remainder of the waveforms shown in Figure 5, as the groundtrack goes between the Borneo mainland and an offshore island, prior to crossing over into the mainland.

Beginning with waveform 14, the tracker is responding more to the off-nadir brighter land return than the at-nadir water return. As a result, the measured range is too long, and the calculated at-nadir sea surface heights corresponding to waveforms 14-20 will be too low.

The waveforms have been retracked for this study; the before/after retracking full-rate SSH results, plotted vs. latitude, are shown in Figure 6. The profile at the top of the figure depicts the SSH from the GDR file, prior to any retracking. The typical near-land effect of misaligned waveform begins at -2.94° latitude, prior to landfall as shown in Figure 4. The SSH derived from the retracking are shown in the bottom profile of the figure. It is apparent that the retracking has added some measurement noise, but the sea surface profile has
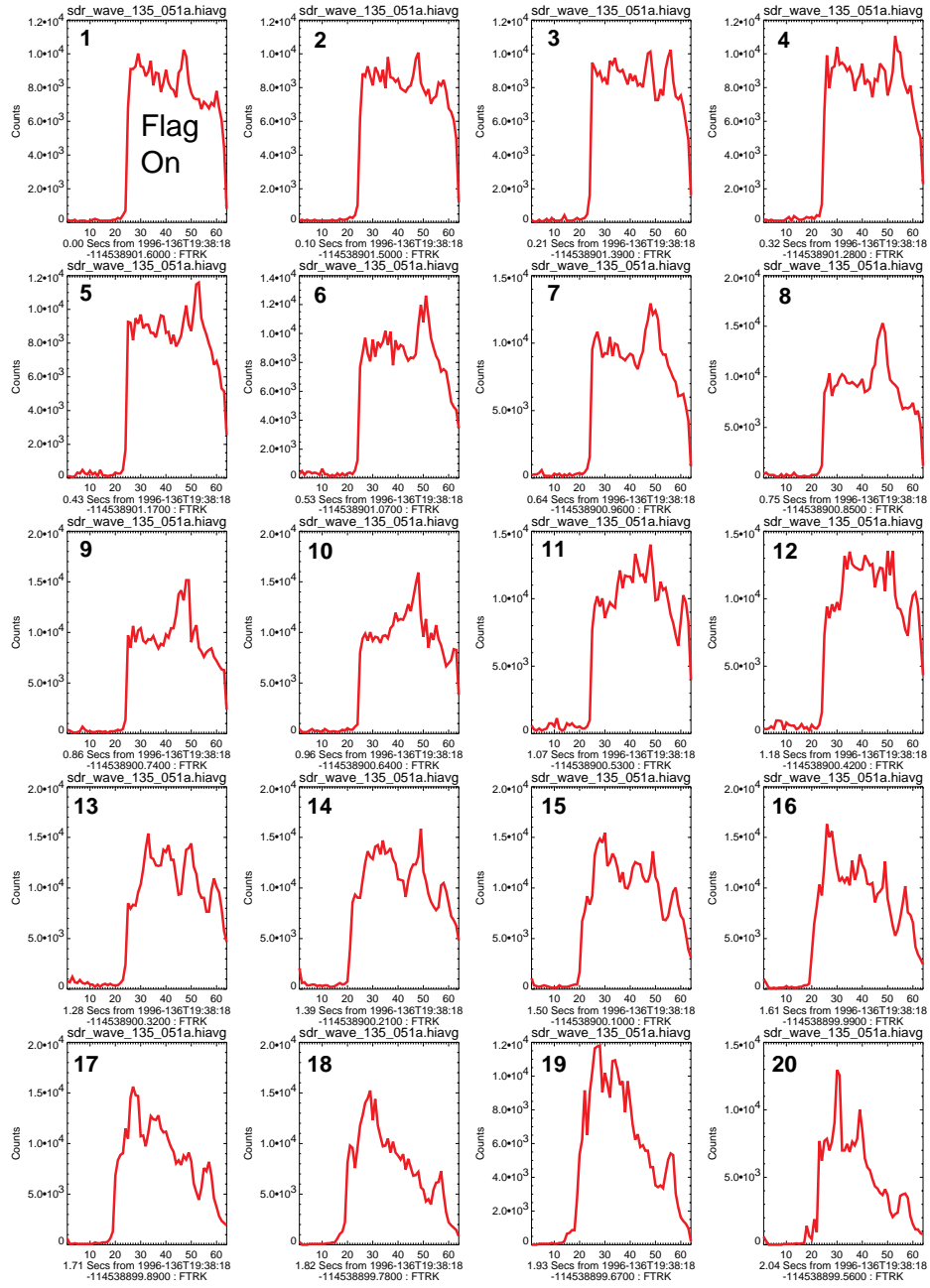
Figure 5: TOPEX Altimeter Waveforms Approaching Southern Borneo
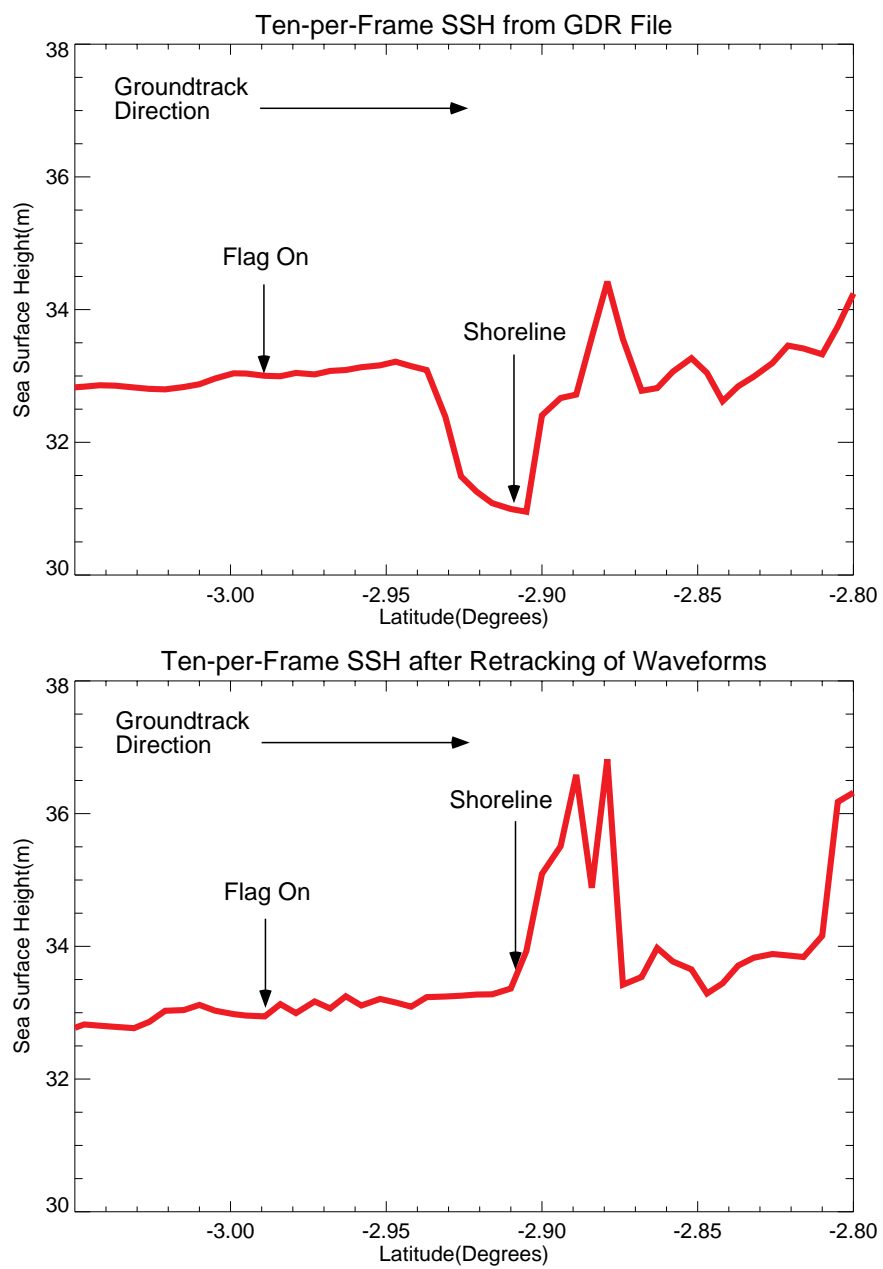
Figure 6: Sea-Surface Heights from Cycle 135/Pass 051 Approaching Southern Borneo, Before/After Retracking

been extended shoreward to -2.91°, the latitude of the southern shoreline of the small island just to the left of the groundtrack. This extension of the sea surface profile is 3.6 km.

The altimeter maintained lock over these southern Borneo lowlands even after the footprint was entirely over land.

New Zealand (Mountainous Topography)

An example of an altimeter groundtrack approaching land, but without intervening small islands, is depicted in Figure 7, where Cycle 075/Pass 10 crosses over New Zealand's very mountainous South Island. In the area where the groundtrack intersects the shoreline, the mountain peaks of the Southern Alps rise to about 1500 m altitude.
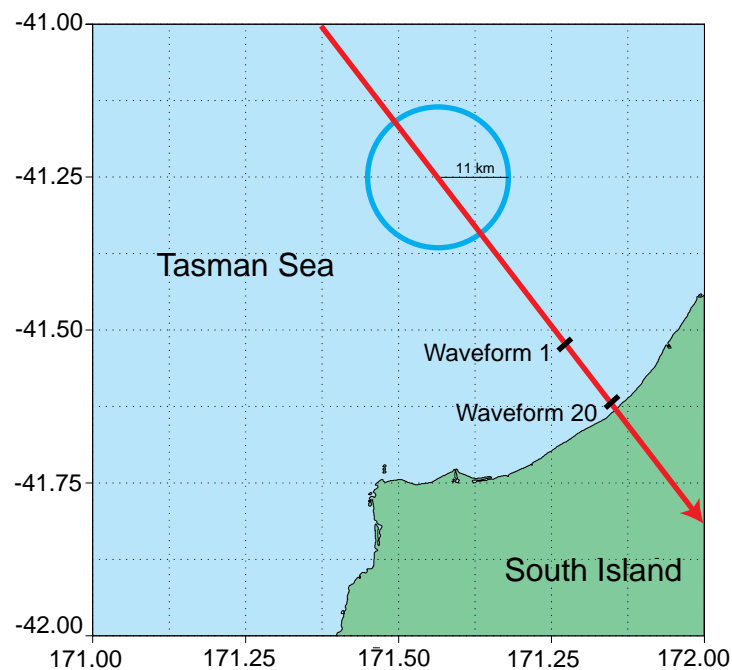
Figure 7: Cycle 075/Pass 010 - Approaching South Island, New Zealand

The initial waveform in Figure 8 is at a distance of 13.6 km from shore; it and the ten waveforms which follow do not contain land reflections. Bit 2 of the Alt_Bad1 flag was set at waveform 11. In the twelfth waveform, at a distance of 6.7 km from land, there appears to be a small land reflection near gate 58. The next waveform, at a distance of 6.1 km, has a very sharp land return. Then, the next five waveforms clearly show initial ocean returns, with the land returns moving closer to the tracking gate. The brightness of the land return has affected the tracker response, and the waveforms have moved to the left (earlier) with
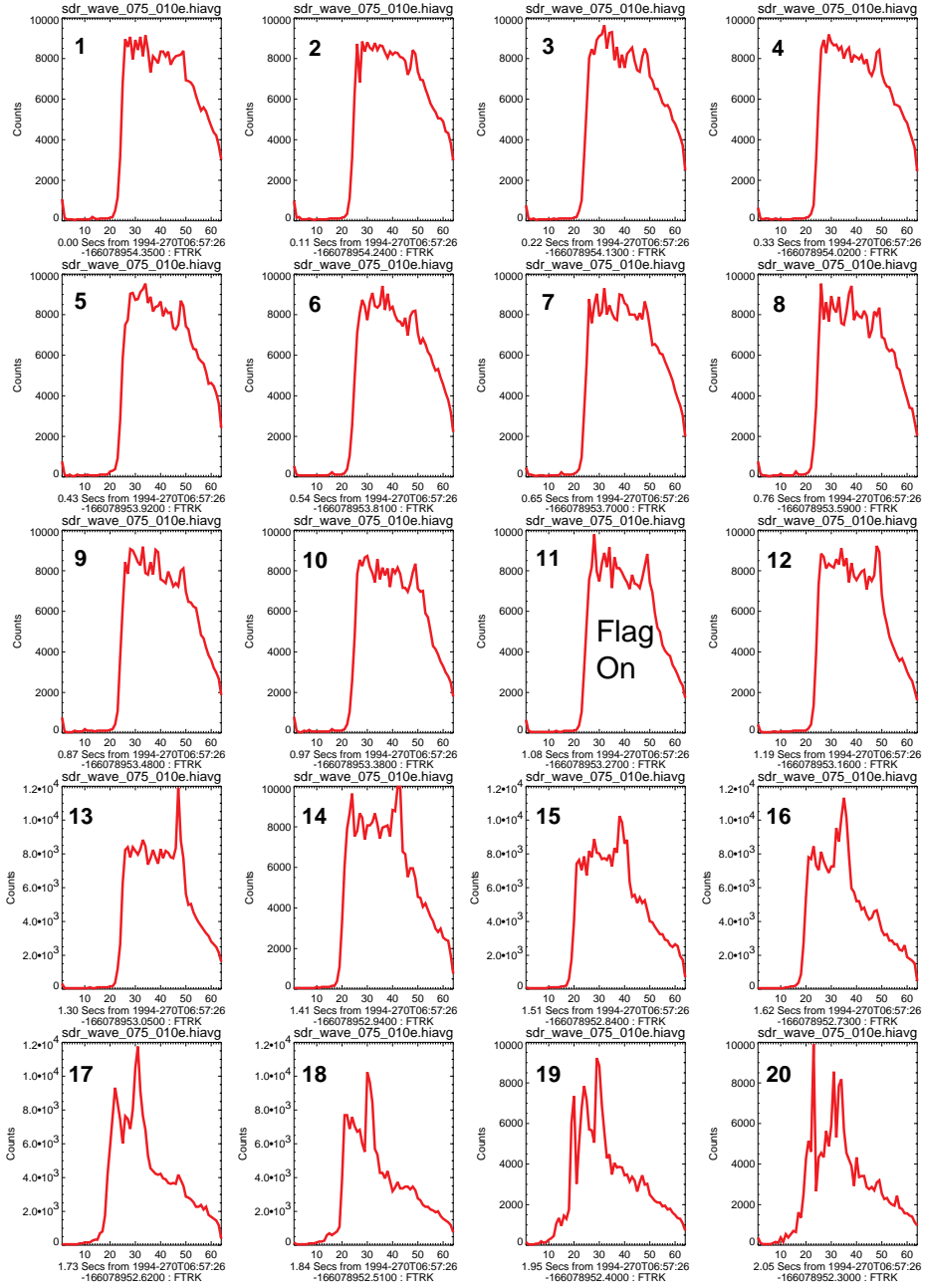
Figure 8: TOPEX Altimeter Waveforms Approaching South Island, New Zealand

respect to the tracking gate. This means that the measured range will be long, and the calculated sea surface heights will be too low. In the next-to-last waveform in Figure 8, at a distance of 2.3 km from the shoreline, the ocean return has become obscured by the land returns, and the ocean surface elevation is no longer recoverable.

The waveforms have been retracked; the before/after retracking full-rate SSH results, plotted vs. latitude, are shown in Figure 9. The profile at the top of the figure depicts the SSH from the GDR file, prior to any retracking. The typical near-land effect of misaligned waveforms begins at -41.57° latitude, prior to landfall as shown in Figure 7. The SSH derived from the retracking are shown in the bottom profile of the figure. It is apparent that the retracking has again added some measurement noise, but the sea surface profile has been extended shoreward to -41.60°, but still short of the shoreline which is at -41.63° latitude. This extension of the sea surface profile, as the result of retracking, is 3.9 km.

The South Island topography is sufficiently rugged that the altimeter never achieved Track Mode during its traverse of the Island.

LAND-TO-WATER

Borneo (Subdued Topography)

TOPEX Pass 140, during Cycle 135 in this example, has a northwest-to-southeast groundtrack which crosses the lowlands of southern Borneo and enters the Java Sea. The groundtrack is shown in Figure 10.

The land-to-water crossover occurs at the second waveform in Figure 11. At this time, the terrain is higher than the ocean with respect to the radar pulse front, and the land reflections appear first in the waveform. This is a marshy area, with standing water, and the waveforms are appropriately specular.The jagged signals which begin around gate 30 in the third waveform are ocean returns. At the time of the seventh waveform, the off-nadir terrain and the at-nadir sea surface are approximately equidistant from the altimeter.

Beginning with the ninth waveform, the initial radar returns are from the sea surface and the land returns move toward the late gates. By waveform 16 (5.6 km from the nearest shoreline) the land returns have disappeared.

Although the sea surface returns are evident in waveforms 9 through 16, these waveforms are misaligned with respect to the tracking gate such that the calculated sea surface height will generally be too low. Retracking of the waveforms would allow for the recovery of the sea heights. After waveform 16, the waveforms appear to be normal open-water returns, and are moving back towards proper alignment. Bit 2 of the Alt_Bad1 flag remains set until the tenth waveform (one frame) after waveform 20.

The waveforms in this area have been retracked; the before/after retracking full-rate SSH results, plotted vs. latitude, are shown in Figure 12. The profile at the top of the figure depicts the SSH from the GDR file, prior to any retracking. The shoreline, as shown in Figure 10, is at latitude -3.05°; the altimeter appears to be tracking fine up to that point. As the groundtrack left the land and went out over the Java Sea, the altimeter continued to track the off-nadir shoreline, resulting in an increasingly long measured range. Then, at latitude -3.10°, the sea surface return gradually began to dominate the waveform, and the tracker moved towards that signal. The tracker over-corrected in the vicinity of -3.14° latitude, and finally stabilized near -3.16° latitude (13.4 km from land).

Ten-per-Frame SSH from GDR File

Groundtrack
Direction

Shoreline

Flag On

Sea Surface Height(m)

Latitude(Degrees)

Ten-per-Frame SSH after Retracking of Waveforms

Groundtrack
Direction

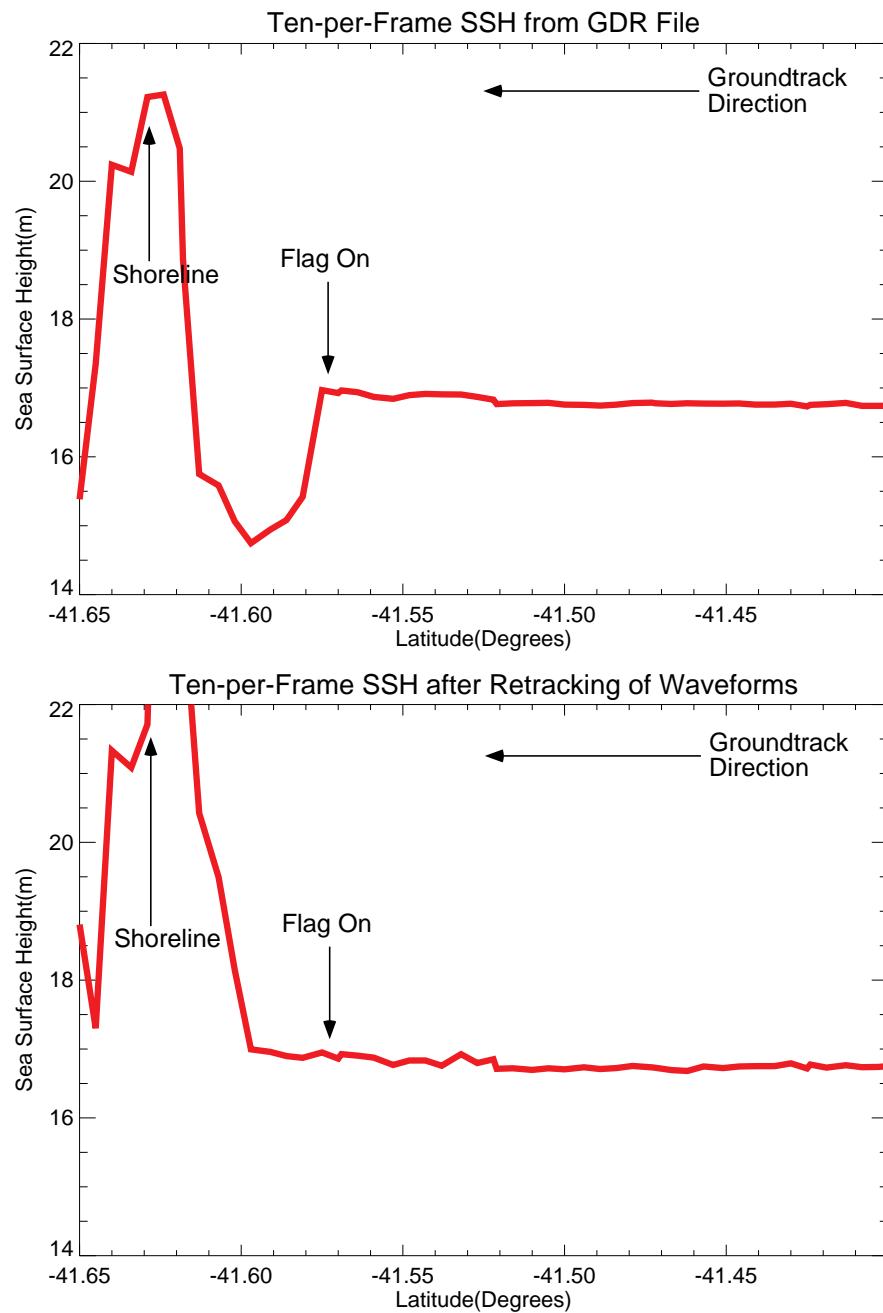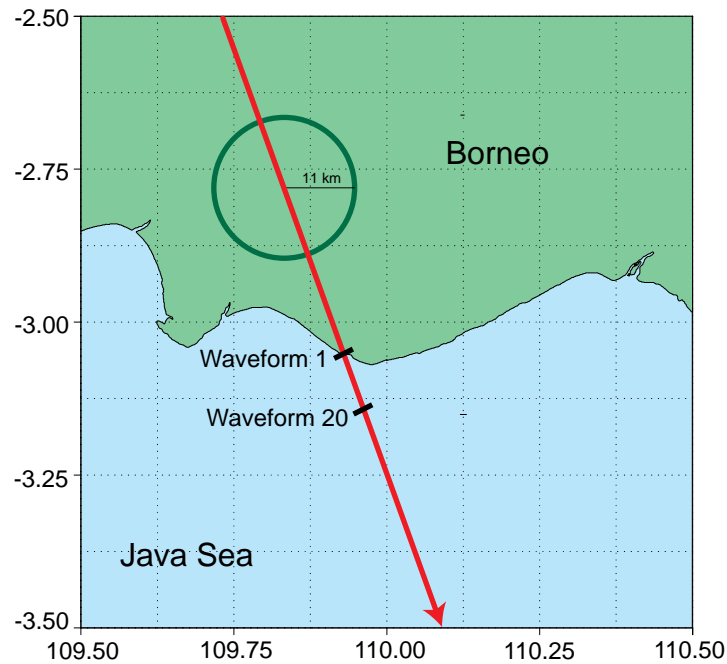Shoreline

Flag On

Sea Surface Height(m)

Latitude(Degrees)

Figure 9: Sea Surface Heights from Cycle 075/Pass 010 Approaching South Island, New Zealand,
Before/After Retracking

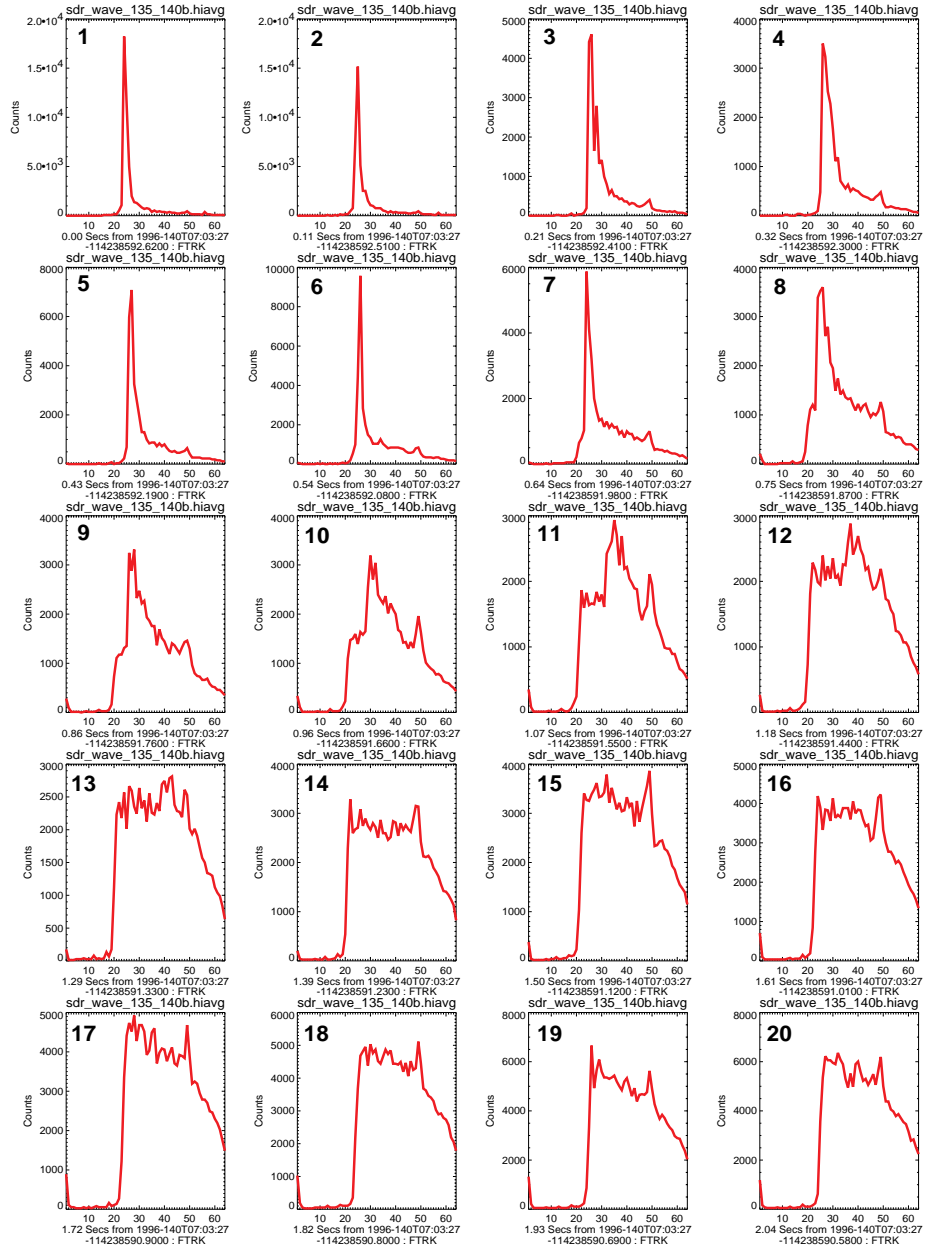Figure 10: Cycle 135/Pass 140 - Leaving Southern Borneo

The SSH derived from the retracking are shown in the bottom profile of Figure 12. The sea surface profile has been extended landward to -3.10°, but still 6.1 km short of the shoreline. This landward extension of the sea surface profile, as the result of retracking, is 7.3 km.

China (Mixed-Terrain)

Cycle 137 Pass 138 traversed the mainland of China in a northwest-to-southeast direction, as shown in Figure 13. It exited the mainland from the Province of Liaoning, near the city of Qinhuangdao, and entered the Bo Hai (Gulf of Chihli) which is an arm of the Yellow Sea. The shoreline is composed of mixed topography, with low hills along the shoreline, leading to mountains to the northwest. In this example, the altimeter was not locked-up on the land, and required approximately 3.5 seconds after the land/water interface to begin Fine-Track Mode.

During most of that 3.5 seconds, the altimeter was in the Coarse-Track Mode. The first two waveforms in Figure 14 occurred at the end of that Coarse Track period. Begin-

Figure 11: TOPEX Altimeter Waveforms Receding from Southern Borneo

Ten-per-Frame SSH from GDR File

Groundtrack
Direction

Shoreline

Flag Off

Sea Surface Height(m)

Latitude(Degrees)

Ten-per-Frame SSH after Retracking of Waveforms

Groundtrack
Direction

Shoreline

Flag Off

Sea Surface Height(m)

Latitude(Degrees)
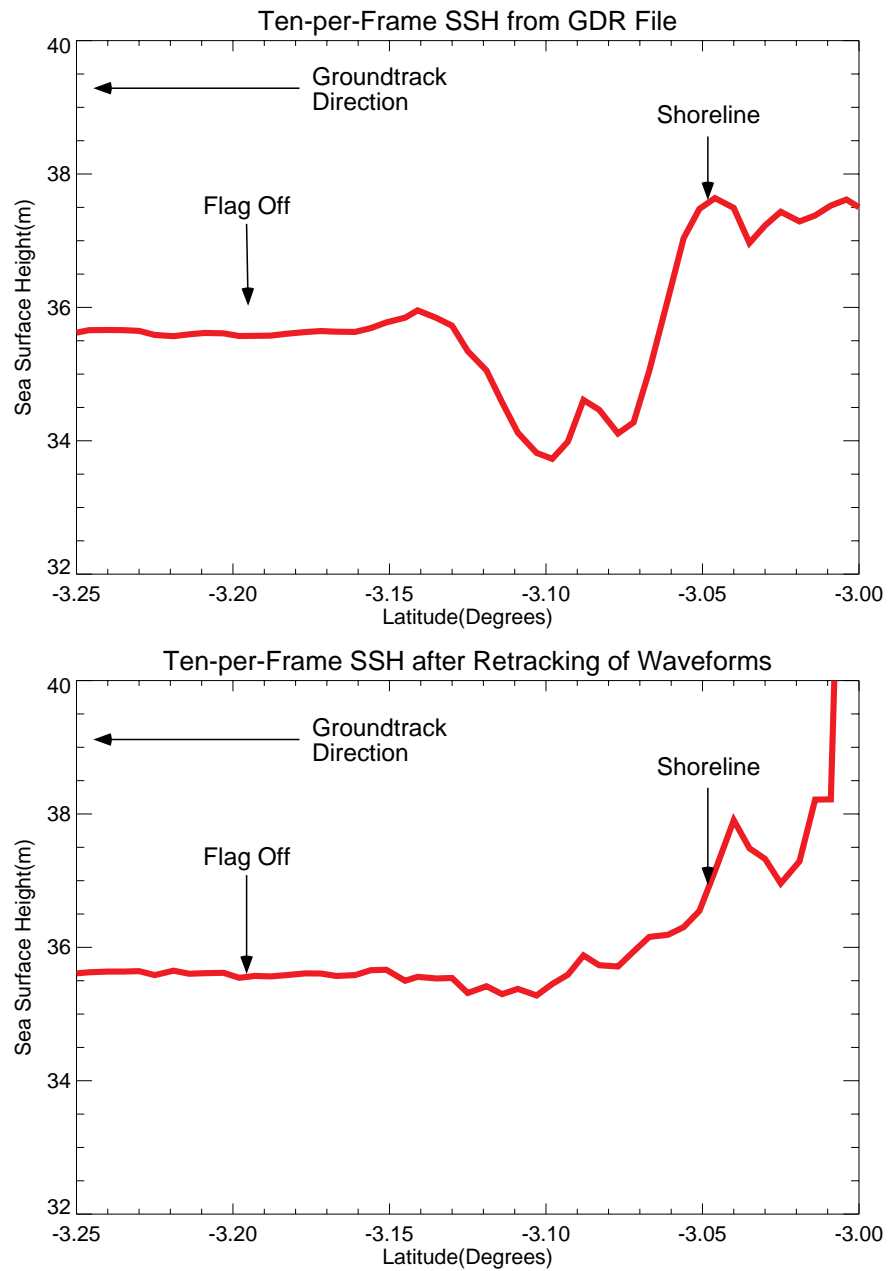
Figure 12: Sea Surface Heights from Cycle 175/Pass 140 Receding from Southern Borneo,
Before/After Retracking
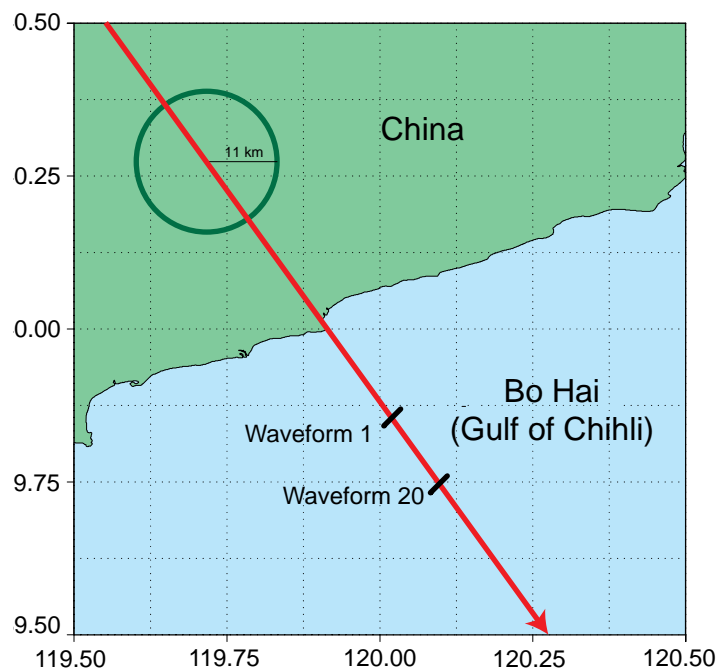
Figure 13: Cycle 137/Pass 138 - Leaving Liaoning Province, China

ning with waveform 3, at a distance of 20.5 km from the shoreline, waveforms appear which are retrackable. During the one-second interval from waveform 3 to waveform 13, the altimeter is locking-up on the sea surface after the mode transition from Coarse Track. Waveforms 3 and 4 are shifted to the right, towards the late gates (range will be too short), while waveforms 5 through 13 are shifted towards the early gates (range will be too long). After waveform 13, which is at a distance of 29.6 km from shore, the waveforms have stabilized and are appropriately aligned with respect to the tracking gate. The waveforms in Figure 14 do not have land returns in them, due to their occurring beyond the 11.0 km footprint radius. Bit 2 of the Alt_Bad1 flag remained set until the third waveform after waveform 20.

The waveforms for this pass in this area have been retracked; the before/after retracking full-rate SSH results, plotted vs. latitude, are shown in Figure 15. The profile at the top of the figure depicts the SSH from the GDR file, prior to any retracking. The shoreline, as shown in Figure 13, is at latitude 40.00°. The altimeter did not lock up on the sea surface until latitude 39.82°. Then the waveforms were misaligned, until latitude 39.775°.

The SSH derived from the retracking are shown in the bottom profile of Figure 15. The sea surface profile has been extended landward to 39.82°, but still 20.5 km short of the
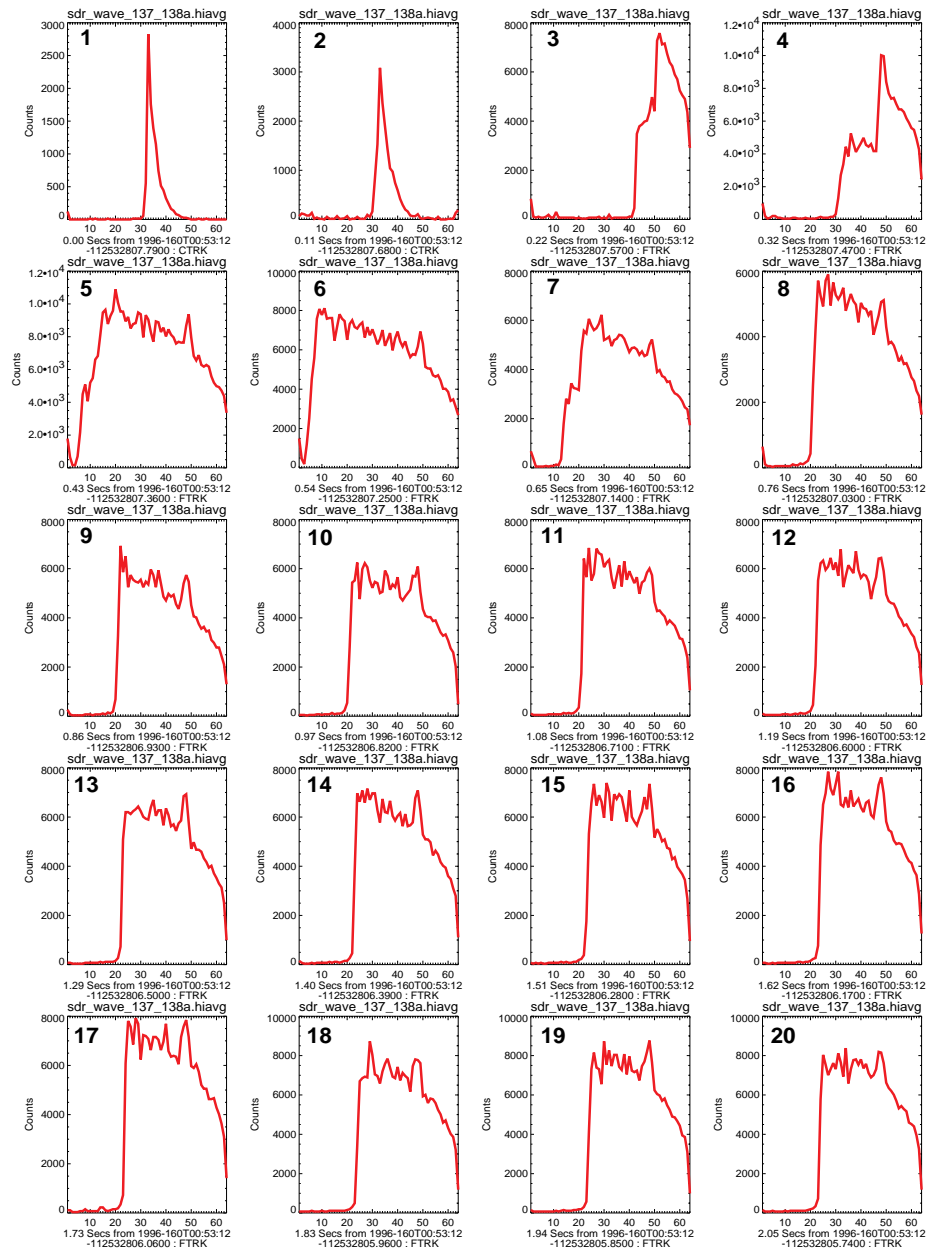
Figure 14: TOPEX Altimeter Waveforms Receding from Liaoning Province, China

shoreline. This landward extension of the sea surface profile, as the result of retracking, is 9.1 km.
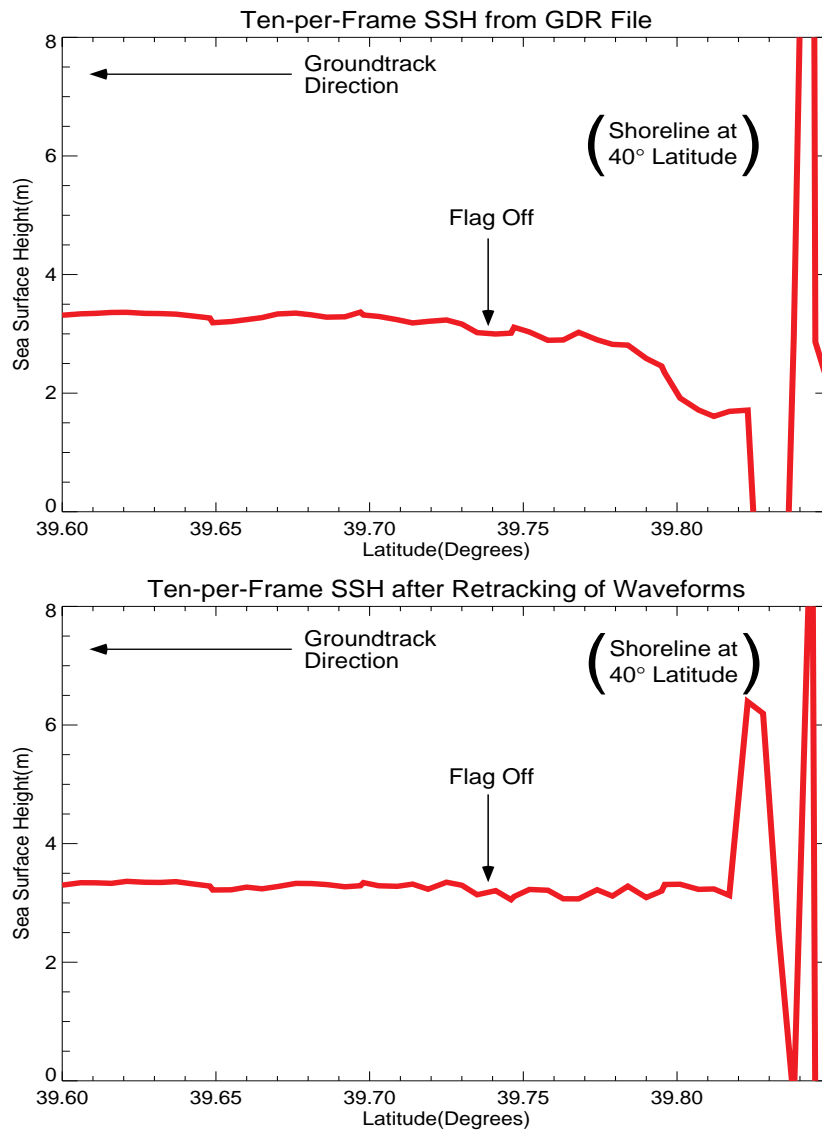
Figure 15: Sea-Surface Heights from Cycle 137/Pass 138 Receding from Liaoning Province, China
Before/After Retracking

5 Synopsis

5.1 Summary of Land Effects

The presence of land affects the altimeter's measurements. The nature of the effects, and the distance from the shoreline at which the measurements are affected, vary with both the type of terrain along the shoreline and whether the altimeter is approaching or going away from the shoreline. This study indicates that the altimeter-derived sea surface topography for a groundtrack, as supplied in GDR files, may be extended several kilometers shoreward by the use of retracking and data corrections. In the case of subdued shoreline topography, such as southern Borneo, the sea surface topography may be extended nearly to the shoreline.

For near-coastal studies, the user of the TOPEX GDR data should monitor bit 2 of the Alt_Bad1 flag. When this bit is set, it indicates that the altimeter waveforms are misshaped or misaligned, and will require retracking.

The water-to-land and land-to-water transitions are discussed in the following.

WATER-TO-LAND

For land effects while approaching a shoreline, Table 1 summarizes our analyses of the full-rate waveforms for nine test cases scattered around the Pacific Rim. The leftmost column of Table 1 identifies the particular study area, and the latitude/longitude of the groundtrack's crossing of the shoreline. The next column provides the TOPEX cycle and pass number which was used in this analysis; the pass groundtracks repeat within ± 1 km crosstrack every 9.92 days. The third column generally describes the nature of the terrain along the shoreline in this area. The fourth column from the left provides the maximum distance from the nearest land that land reflections are discerned in this area's waveforms, based on a personal inspection of the full-rate waveforms. Land reflections appeared as early as 10.8 km from land (near the edge of the 11.0 km footprint) for the Japan study area, and as late as 5.6 km for Yangma Dao, China.

The next column is the maximum distance from the shoreline at which bit 2 of the Alt_Bad1 flag is set. As stated earlier, this distance is equal to or greater than the distance that land returns appear in the individual waveforms, as this flag is set for an entire frame even though not all of the waveforms in the frame may have been affected. This distance from land will vary from cycle-to-cycle because the inter-cycle frame boundaries are not geographically aligned.

The sixth column from the left lists the distances from land for which the high-rate waveforms could be retracked to recover the sea surface topography. Since these are within the Alt_Bad1 flagged areas, new SSH corrections for DR(SWH/Att)_K and Iono_Corr need to be applied as described earlier in steps 4 and 5 of Section 3.

The seventh column provides the distances from the shoreline for which the sea surface heights are not recoverable by retracking. This is the result of the land returns occurring in the early gates of the waveforms, prior to the sea surface returns. For these water-to-land transitions, the ocean surface topography is recoverable all the way to the shoreline only for the three subdued topography areas of 1) southern Borneo, 2) Isle de Santa Margarita off the coast of Baja California, and 3) Yangma Dao island off the coast of China's

Shandong Province. Based on this study, the sea surface topography is recoverable to a distance of about two kilometers from a shoreline. The selected threshold for each area's retracking in shown in the last column.

LAND-TO-WATER

For altimeter groundtracks receding from land, the results are tabulated in Table 2. The column descriptions are the same as for Table 1. In column four of Table 2, the maximum distance at which land reflections appear in the waveforms are about the same as in Table 1, except for the areas of Baja California, Magadan, Russia, and China's Liaoning Province, for which there were no land reflections. In these three areas, the altimeter did not lock-up on the sea surface until the groundtrack was beyond the distance at which the land reflections would have appeared. These three areas nonetheless will benefit from waveform retracking due to the altimeter tracker's requiring about a second of time (ten waveforms) to settle-out after reacquiring the sea surface. The Alt_Bad1 flag is set in these three areas due to the waveforms not being stabilized with respect to the tracking gate during the settling-out period. In none of these nine areas was the sea surface recoverable all the way to the shoreline.

Table 1: Approaching a Shoreline

Study Area and Latitude/Longitude of Water-to-Land Transition	TOPEX Altimeter Cycle/Pass	Type of Shoreline Terrain	Max. Distance Land Appears in Ocean Waveform (km)	Max. Distance Alt_Bad1 Flag is Set (km)	Waveform Retracking and Correction Needed (km)	Data Not Recoverable Distance from Shoreline (km)	Threshold for Retracking (counts)
Borneo (southern) 2.9^{o}S,110.2^{o}E	Cycle 135 Pass 051	Low, swampy	9.6	9.6	0 - 9.6	none	2000
Honshu, Japan 36.5^{o}N,136.5^{o}E	Cycle 099 Pass 010	Hilly	10.8	15.7	5.4 - 15.7	0 - 5.4	2500
South Island, New Zealand 41.6^{o}S,171.9^{o}E	Cycle 075 Pass 010	Mountain-ous	6.7	7.5	2.3 - 7.5	0 - 2.3	2000
Vancouver Island, British Columbia, Canada 49.2^{o}N,234.0^{o}E	Cycle 137 Pass 095	Rugged Islands	6.4	11.6	2.3 - 11.6	0 - 2.3	1500
Isle de Santa Margarita, Baja California, Mex-ico 24.3^{o}N,248.3^{o}E	Cycle 137 Pass 169	Low-lying	7.0	8.1	0 - 8.1	none	1500
Sonora, Mexico 27.2^{o}N,249.6^{o}E	Cycle 137 Pass 169	Marshy	7.5	12.8	1.2 - 12.8	0 - 1.2	1500
Chile (central) 38.8^{o}S,286.6^{o}E	Cycle 137 Pass 139	Rugged	8.2	9.8	2.5 - 9.8	0 - 2.5	500
Kamchatka Pen-insula, Russia 56.2^{o}N,155.8^{o}E	Cycle 137 Pass 058	Marshy	10.4	10.4	3.4 - 10.4	0 - 3.4	1000
Yangma Dao (Island), Shandong Prov-ince, China 37.5^{o}N,121.6^{o}E	Cycle 137 Pass 138	Low-lying	5.6	12.2	0 - 12.2	none	1500

Table 2: Receding from a Shoreline

Study Area and Latitude/Longitude of Water-to-Land Transition	TOPEX Altimeter Cycle/Pass	Type of Shoreline Terrain	Max. Distance Land Appears in Ocean Waveform (km)	Max. Distance Alt_Bad1 Flag is Set (km)	Waveform Retracking and Correction Needed (km)	Data Not Recoverable Distance from Shoreline (km)	Threshold for Retracking (counts)
Borneo (southern) 3.1S°,110.9°E	Cycle 135 Pass 140	Low, swampy	5.6	13.4	6.1 - 13.4	0 - 6.1	1000
Honshu, Japan 34.7°N,137.6°E	Cycle 099 Pass 010	Mixed Terrain	7.1	12.1	5.8 - 12.1	0 - 5.8	1000
South Island, New Zealand 43.1°S,173.0°E	Cycle 075 Pass 010	Mountainous	8.8	9.3	6.3 - 9.3	0 - 6.3	2000
Vladivostok, Russia 43.0°N,131.8°E	Cycle 099 Pass 010	Mixed Terrain	5.9	12.2	1.9 - 12.2	0 - 1.9	1500
Baja California, Mexico 25.6°N,248.8°E	Cycle 137 Pass 169	Mountainous	n/a	15.7	10.4 - 15.7	0 - 10.4	1500
Magadan,Russia 59.5°N,149.0°E	Cycle 137 Pass 058	Rugged	n/a	15.7	10.2 - 15.7	0 - 10.2	2000
Kamchatka Peninsula, Russia 53.7°S,159.8°E	Cycle 137 Pass 058	Mountainous	7.5	7.5	5.8 - 7.5	0 - 5.8	1000
Liaoning Province, China 40.0°N,119.9°E	Cycle 137 Pass 138	Low-lying	n/a	34.8	20.5 - 34.8	0 - 20.5	1500
Shandong Province, China 36.9°N,122.0°E	Cycle 137 Pass 138	Low-lying	4.1	14.5	2.8 - 14.5	0 - 2.8	500

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Source of Coastline Information

The coastline configurations in this document are extracted from the "Medium-Resolution Vector Shoreline" database, on a CD-ROM obtained from NOAA's Office of Ocean Resources, Conservation, and Assessment; this office is a part of the National Ocean Service. This medium-resolution database is suitable for maps at the scale of 1:250,000. Such shoreline maps are also extractable interactively from the database, on the Internet at URL <http://crusty.er.usgs.gov/coast/getcoast.html>.